Characteristics of a cascade arc used as a light source for spectroscopic techniques

CHARACTERISTICS OF A CASCADE ARC USED AS A LIGHT SOURCE FOR SPECTROSCOPIC TECHNIQUES.

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ABSTRACT

We have determined the characteristic quantities (the electron temperature and the electron density) of an argon plasma in a cascade arc (diameter 2 mm) for a pressure range of 1 – 8 Bar and a current range of 20 – 70 Ampere from absolute continuum measurements assuming LTE. The wavelength region covers 380 up to 800 nm. Comparison with theory shows that the plasma is close to Local Thermal Equilibrium and prediction of the absolute intensity as a function of the wavelength is possible within 10%. Deviations of the theoretical Biberman factors (according to Hoffsaes) have been measured in the covered wavelength region. Comparison with experimental results of others confirm our measurements.

1. Introduction

Continuum light sources that cover a large spectral range are applied in several analytical techniques. Depending on the nature of the technique the range of interest may cover the UV, visible or IR part of the spectrum. In the following we will focus on spectroscopic ellipsometry and IR absorption spectroscopy.

Spectroscopic ellipsometers that operate in the UV–visible range usually apply a Xenon short arc as a light source. This kind of high pressure enveloped arcs has a number of features that inhibit its flexible use. The light that is emitted is slightly polarized by the curved quartz envelope. Therefore the dispersive element (usually a monochromator) has to be placed directly after the light source and the complete system has to be operated in the dark. Furthermore, because of the large opening angle a complex optical system is needed to achieve an intense light beam with a small aperture (as is necessary for ellipsometry).

A cascade arc does not have these disadvantages. Since the light exits through flat windows no polarization occurs. Furthermore other materials than quartz (e.g. LiF, BaF_2, MgF_2 etc) can be used as a window in order to expand the spectral range. The aperture of the light beam is relatively small (50 mrad), but the intensity in this small aperture is very large as will be shown below. Because of the large length of the plasma (40 to 60 mm) the sensitivity of the ellipsometer to defocusing effects (dispersion of the material of of the several elements of the optical system) reduces substantially. Furthermore the alignment of the ellipsometer can be done easily by directing a He–Ne laser beam through the plasma channel of the axially symmetric arc [1,2,3].

For IR absorption spectroscopy, using for instance a Fourier transform infrared spectrometer (FTIR), usually a Globar source is used. The radiating area of the Globar is rather large (several square cm's) and its temperature is relatively low (1600 K).

A cascade arc plasma has a temperature of roughly 14000 K which offers an increase in intensity by at least a factor 20–200 depending on the wavelength. This implies an increase of the signal–to–noise ratio with the same factor. If a cascade arc is used in an FTIR than also the small diameter of the plasma channel (2 mm) and the small aperture are of importance.

To optimize the arc plasma in a certain wavelength region one has to know the characteristics of the cascade arc (e.g. the relation between the external parameters such as current and pressure vs. electron density and electron temperature).

In section 2 we will discuss the basic emission theory of arc plasmas, in section 3 the cascade arc will be treated and finally in section 4 some results and conclusions about the use of the cascade arc will be given.

2. THE INTENSITY OF THE CASCADE ARC

High pressure discharges are well described by theory. Quantities such as electron density, electron temperature and emission of line or continuum radiation can be calculated with high accuracy.

At high electron densities (> 10^{22} m^{-3}) and electron temperatures (> 10000 K) the line emission is negligible compared to the continuum emission. Our cascade arc discharge has an electron temperature of approximately 15000 K and electron densities a few times 10^{23} m^{-3}. Therefore, in calculating the intensity emitted from the cascade arc only the continuum emission has to be considered.

The continuum emission of the discharge is governed by the following expressions [4]:

$$\epsilon = \epsilon_{fb} + \epsilon_{ff}^{ei} + \epsilon_{ff}^{ea} \tag{1}$$

whererin :

$$\epsilon_{ff}^{ei} = \sum_z \frac{C_1}{\lambda^2} \frac{n_e n_z}{\sqrt{T_e}} z^2 \, exp\left[-\frac{hc}{\lambda k T_e}\right] \xi_{ff}(\lambda, T_e, z) \tag{2}$$

$$\epsilon_{ff}^{ea} = \frac{C_2}{\lambda^2} \cdot n_e n_0 \cdot \sqrt{T^3} \cdot Q(T_e) \cdot [(1 + \frac{hc}{\lambda k T_e})^2 + 1] \cdot exp(\frac{-hc}{\lambda k T_e}) \tag{3}$$

and

$$\epsilon_{fb} = \sum_z \frac{C_1}{\lambda^2} \frac{n_e n_z}{\sqrt{T_e}} z^2 \left[1 - exp\left[-\frac{hc}{\lambda k T_e}\right]\right] \frac{g_{z,1}}{U_z} \xi_{fb}(\lambda, T_e, z) \tag{4}$$

In these expressions the symbols represent the following:

- ϵ_{ff}^{ei} : free–free radiation caused by electron–ion interaction,
- ϵ_{ff}^{ea} : free–free radiation caused by electron–atom interaction,
- ϵ_{fb} : free–bound radiation,
- λ : the wave length of the radiation,
- C_1 : the *ei* continuum constant ($1.63\ 10^{-43}\ Wm^4K^{0.5}sr^{-1}$),
- C_2 : the *ea* continuum constant ($1.026\ 10^{-34}\ W^4K^{1.5}sr^{-1}$),
- $Q(T_e)$: the cross section for electron atom interaction
- h : the Planck constant ($6.626\ 10^{34}\ J/Hz$),
- n_e : the electron density,
- n_z : the density of the ground state z ($z=0,1,2,..$),
- T_e : the electron temperature,
- ξ_{ff} : the Biberman factor for free–free radiation [5],
- ξ_{fb} : the Biberman factor for free–bound radiation [6].

The contributions of electron–atom, electron–twofold–ionized atom radiation are neglible [7,8].

The intensity emitted by the cascade arc is described by the expression

$$I = S\,[1 - exp(-\epsilon l/S)]\,, \qquad [\mathrm{Wm^{-3}sr^{-1}}] \qquad (5).$$

where S is given by the Planck formula

$$S_\lambda = \frac{2hc^2}{\lambda^5}\left[\, exp\left[\frac{h\,c}{\lambda k T_e}\right] - 1\right]^{-1}, \qquad [\mathrm{Wm^{-3}sr^{-1}}] \qquad (6).$$

ϵ is the total emission, viz. the free–free and free–bound emission, and l the length of the discharge.

From the measurements we obtain a absolute value for I : I_{meas}. With relation (5) we can calculate the absolute total emission ϵ : ϵ_{meas}. If we assume LTE conditions (which is allowed in our temperature range ; only slight deviations from LTE , the so called PLTE are expected) we can express n_a, n_1 and n_2 in terms of n_e with the help of the Saha equation and quasi–neutrality :

$$n_e = n_1 + 2n_2 \qquad (7)$$

The unknown parameters are now n_e and T_e. With Daltons law stating that

$$p = \sum_i n_i\, kT_i \;, \qquad (8)$$

and the absolute pressure p_{meas} and ϵ_{meas} two equations are obtained.With successive substitution n_e and T_e can be solved.

3. The Cascaded Arc

The cascade arc consists of three major sections, a cathode section, an anode section and a plate section inbetween. The plate section, which holds five copper plates stacked into a cascade, gives the cascade arc its name. The whole system has a cylindrical geometry with the plasma channel located on the symmetry axis. A schematic drawing of the arc is given in Fig. 3.2.

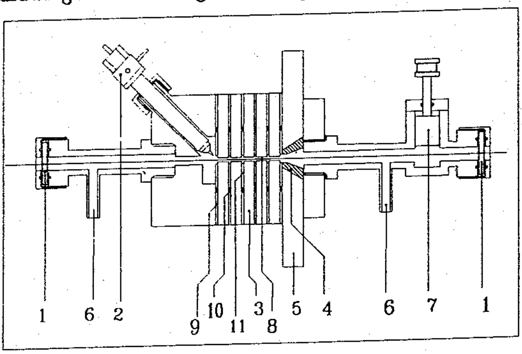

Fig. 3.2. : The cascade arc.
1: window (LiF),
2: cathode (3×),
3: cascade plates,
4: anode plate,
5: anode insert,
6: gas inlet and outlet,
7: shutter,
8: plasma/gas channel,
9: PVC spacer,
10: O ring,
11: Boron Nitride disk.

All sections are watercooled by means of internal water channels. The sections and the plates themselves are electrically insulated by PVC–spacers. Boron–Nitride disks protect the O–rings (see Fig. 1) from damage caused by UV radiation emitted in the plasma channel. The cathode section contains three independent cathodes with sharp–pointed Tungsten–Thorium tips. The anode section holds the conical anode insert. Normally argon is used as the discharge gas at a flow of roughly 1 scc/s. Also a brass rod can be placed before the exit window to protect the window during startup of the arc. A plasma beam would hit the window.

4. RESULTS AND DISCUSSIONS

In this section the results and discussions of the calculations and measurements are given. In figure 4.1 the calculated intensity of the cascade arc is plotted for two different pressures. Also a 1000 Watt Xenon short arc and a Globar of 1600 K are shown.

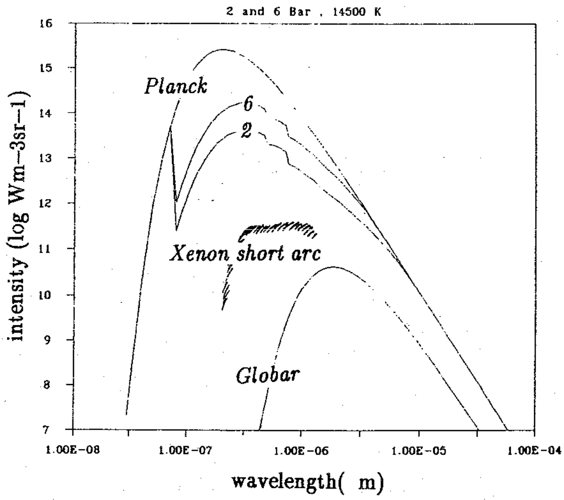

Fig. 4.1. The calculated intensity of a cascade arc with pressures of 2 and 4 Bar and a temperature of 14500 K. Also the Black body (Planck) radiation of 14500 K, a 1000 W Xenon short arc and a 1600 K Globar are given.

In figure 4.2 the visible spectrum of the arc plasma is given for 4 Bar and several currents.

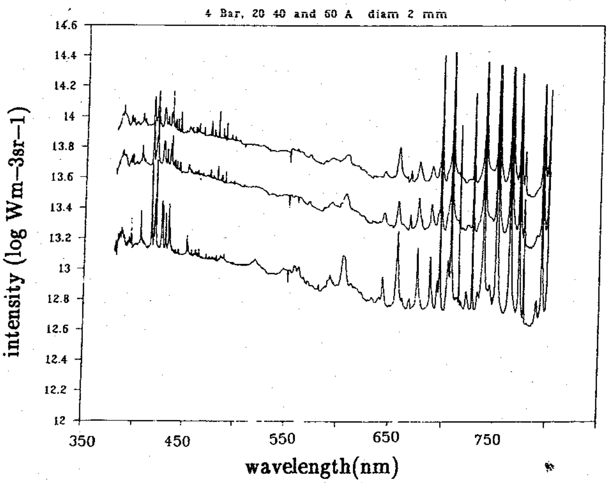

Fig 4.2. : The measured absolute intensity of a cascade arc between 380 and 800 nm for 4 Bar. 20, 40 and 60 Ampere.

From the absolute intensities in figure 4.2. using the procedure described in the last part of section 2, the electron density and the electron temperature are calculated for several wavelengths between 380 and 800 nm. In figure 4.3 the electron density is shown for the situation of 4 Bar and three currents (20, 40 and 60 A). As can be seen from this figure a systematic behavior occurs. The same behavior is noticed for all pressures and also for the electron temperatures , as can be expected.

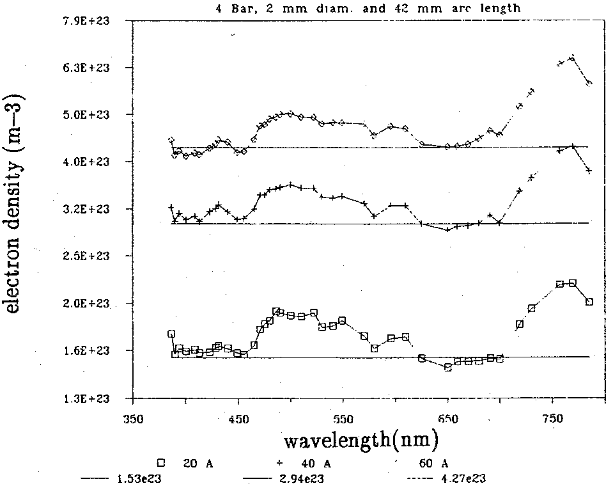

Fig. 4.3 : The measured (points) and LTE– calculated (lines) electron density as a function of the wavelength for a arc plasma of 4 Bar and several currents (20, 40 and 60 A).

The difference between the calculated electron densities and the expected straight line is mainly due to our usage of theoretical free–bound Biberman factors according to Hoffsaes [6]. In figure 4.6 the measured emission is divided by a calculated emissivity with parameters n_e and T_e equal to those at 650 nm. It is clear that the result equals a division of ξ_{total} measured by ξ_{total} according to Hoffsaes. Since ξ_{fb} accounts for more than 90 % of the total

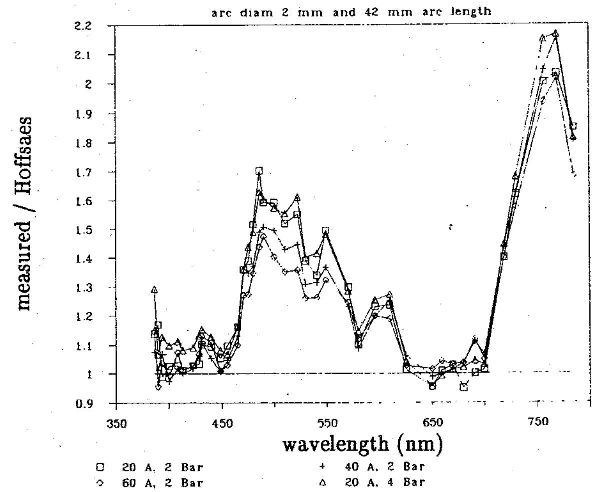

Fig. 4.4 : The free–bound Biberman factor (one–fold ionized) measured in relation the Hoffsaes.

emission in this wavelength region it can be assumed that the figure displays the division of the free–bound factors.

At 500 nm the deviation amounts almost 70 %. Above 700 nm the deviation rises to values of more than 100 %. However , in this region also some line emission contributes to the continuum emission. Only at 785 nm a significant line free spectrum is found. The deviation is here approximately 80 %.

In figure 4.5 the electron density (4 Bar and 20 A, other parameters show the same results) is calculated with the use of the free–bound factors according Hoffsaes (theoretical) , Schulz–Gulde (experimental) [9] and Schnehage (experimental) [10]. The electron densities calculated with Schnehage give the most realistic results (most indepent of the wavelength); 15 % variation (constant slope) against 30 % (max/min) for Hoffsaes. Those calculated with free–bound factors from Schulz–Gulde show a somewhat chaotic behavior; especially where Hoffsaes and Schnehage give smooth results (380 to 460 nm).

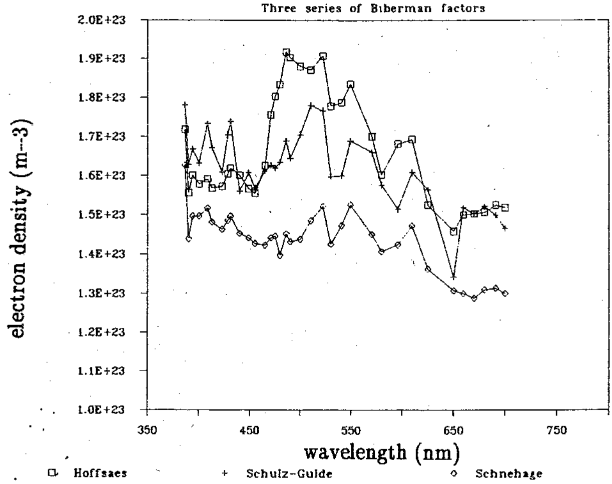

Fig. 4.5 : The electron density calculated with free–bound factors of Hoffsaes, Schulz–Gulde and Schnehage.

The variations in the free–bound factors of Schulz–Gulde are within his claimed accuracy (20 %). If we take this into account, the values of Schulz–Gulde and Schnehage are the same except for a constant difference of about 10 %. According to our measurements the slope of the free–bound factors to higher wavelengths should be less.

A final conclusion concerning the question which Biberman factors are correct has yet to be made. More measurements will be done with line profiles to determine the electron density from a different approach (here LTE was used).

The use of the cascade arc as a lightsource for spectroscopic ellipsometry and IR–interferometry gives good results, resp. a extension to 10 μm and S/N improvements of 20–200 (wavelength dependent).

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